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Paper Bags vis-à-vis LDPE Bags: Gleanings from Peer-reviewed E-LCA Publications

Torby papierowe a torby foliowe LDPE: wnioski z recenzowanych publikacji na temat oceny cyklu życia (E-LCA)

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Abstract: Fossil-plastics or paper? Or for that matter, bio-plastics and paper? This is a well-entrenched question in academic research, industrial, social and policy-making circles. As environmental life-cycle analyses (or more appropriately, sustainability analyses) show time and again, no single product or process or mode of operation is a 'total villain'. There are goods and bads, and at times, more of the one than the other. This paper, which is based on a course-report written by the first author at Karlstad University (Sweden), restricts itself to a review of publications which have opted to compare paper bags with low density polyethylene (LDPE) plastic bags, on the basis of their environmental impacts. Environmental impact categories include the global warming potential, energy demand, fossil fuel depletion, water usage, acidification, eutrophication, and a range of toxicities – human, terrestrial, freshwater-aquatic and marine-aquatic. The articles were obtained through Google Scholar, read and reviewed to glean the results presented therein. The 'What', 'How' and 'Where', so to say were studied carefully to understand the reasons behind any differences or similarities detected. On the basis of this focused review, even though no new knowledge is being added, the common belief that the paper bag is environmentally superior to the LDPE alternative is further consolidated. However, if one focuses on water usage and would assign a high weightage to that environmental impact, LDPE perhaps may score a few 'brownie points' over paper. One must also not forget that plastics (LDPE in this instance) can be recycled without significant deterioration in its functional properties. In a circular economy (the bioeconomy part of which gradually will expand over time), while introducing more and more bio-based products into the technosphere by way of trans-materialization is recommended, plastics will still continue to exist – albeit in much smaller amounts – and it would be perfectly fine if the degree of recycling is augmented significantly. Speaking of a holistic sustainability analysis, the socio-economic aspects of a choice between LDPE and paper bags must also be factored in, and studied. Much-desired change happens when the top-down meets the bottom-up somewhere midway.

Keywords: Circular economy, E-LCA, global warming potential, LDPE, paper bags, plastic bags, water usage

Streszczenie: Tworzywa sztuczne pochodzenia kopalnego czy papier? A może biotworzywa i papier? Pytanie to stale pojawia się w kręgach akademickich, badawczych, przemysłowych, społecznych i politycznych. Jak wielokrotnie wykazały środowiskowe analizy cyklu życia (lub dokładniej, analizy zrównoważonego rozwoju), w kwestiach środowiskowych żaden pojedynczy produkt, proces czy sposób działania nie może być uznany za „jedynego winowajcę". Wszystkie rozwiązania niosą ze sobą zarówno dobre, jak i złe skutki, a tylko w niektórych przypadkach jedne przeważają nad drugimi. Niniejszy artykuł, bazujący na sprawozdaniu z kursu napisanym przez pierwszego z autorów na Uniwersytecie w Karlstad (Szwecja), stanowi przegląd publikacji na temat porównania wpływu toreb papierowych oraz plastikowych toreb z polietylenu o niskiej gęstości (LDPE) na środowisko. Kategorie wpływu na środowisko obejmują potencjał tworzenia efektu cieplarnianego, zapotrzebowanie na energię, wyczerpywanie paliw kopalnych, zużycie wody, zakwaszanie, eutrofizację oraz toksyczność dla ludzi, oraz ekosystemów lądowych, słodkowodnych i morskich. Przegląd literatury mający na celu zebranie przedstawionych wyników badań obejmował artykuły wyszukane za pomocą Google Scholar. Aby w pełni zrozumieć przyczyny dostrzeżonych różnic czy podobieństw przeprowadzono uważną analizę odpowiadając na pytania „Co", „Jak" i „Gdzie". Mimo że ten ukierunkowany przegląd literatury przedmiotu nie wnosi żadnej nowej wiedzy, to jednak służy ugruntowaniu powszechnego przekonania o mniejszej szkodliwości toreb papierowych dla środowiska, w porównaniu z LDPE. Jeśli jednak za istotne kryterium wpływu na środowisko przyjmiemy zużycie wody, torby LDPE zyskują w porównaniu z papierowymi kilka przysłowiowych punktów. Jednocześnie, nie można zapominać, że tworzywa sztuczne (w tym wypadku LDPE) można poddać recyklingowi bez znaczącego pogorszenia ich właściwości użytkowych, a chociaż w gospodarce o obiegu zamkniętym (w której biogospodarka będzie z czasem zyskiwać na znaczeniu) zaleca się wprowadzanie do technosfery coraz większej liczby bioproduktów na drodze transmaterializacji, to jednak tworzywa sztuczne zawsze będą wykorzystywane – choć oczywiście w znacznie mniejszych ilościach – dlatego zwiększenie stopnia recyklingu jest jak najbardziej pożądane. W całościowej analizie zgodności cyklu życia toreb LDPE i toreb papierowych z zasadami zrównoważonego rozwoju, należy również uwzględnić aspekty społeczno-ekonomiczne. Pożądane zmiany zachodzą wtedy, gdy odgórne podejście spotyka się gdzieś w połowie drogi z tym oddolnym.

Słowa kluczowe: Gospodarka o obiegu zamkniętym, E-LCA, współczynnik ocieplenia globalnego, LDPE, torby papierowe, torby foliowe, zużycie wody

Introduction and Methodology

In 2021, global plastic resin production amounted to 390.7 million metric tons according to Statista (2023). Plastics have been ubiquitous over the years, on account of a host of favourable properties – low cost, low mass (lightweight), mechanically and thermally suitable for the applications they are put to. While these functional, use-phase advantages cannot be overlooked, the upstream environmental impacts (global warming in particular, and of relevance to the sustainable development goal # 13 Climate Action) ought not to be pushed under the carpet. On the downstream, irresponsible end-of-life handling of plastics has led to the accumulation of microplastics in the aquatic and terrestrial environments and hence thwarting advances towards SDG# 14 Life below water. Sustainability of production and consumption (SDG# 12) is also under the scanner when one considers the fact that only 79% of all plastic waste ever produced, as of 2015, where disposed in landfills. Dumps or in the environment. Only 9% were recycled, according to the United Nations Environment Programme 2018.

Narrowing the focus down to Europe, as reported by Gómez & Escobar (2022), it is noteworthy that 100 billion plastic bags (to carry groceries back home from supermarkets) are used annually on the continent according to the European Union (EU). These have excellent mechanical properties, are waterproof and hygienic, and inexpensive to boot. But, as is known, being petroleum-based, they have a high embedded carbon footprint. To compound the culpability, they are non-biodegradable and often have a very short functional lifetime Within the EU, the goal is to reduce the number of plastic bags per person per year to 40. In 2019, this metric was 74 in Sweden. In 2020, courtesy the plastic tax (economic 'stick') which was levied in the country, the per-capita consumption dropped to a remarkable low of 14 in 2019, as gathered from Naturvårdsverket (n.d.a).

While dematerializing by availing of policy instruments like taxes is one way to go, trans-materializing simultaneously by generating awareness about, and promoting the adoption of alternatives like paper bags, biodegradable (bio-plastic) bags, reusable bags, or cotton-cloth bags, in a circular bio-economy of the future (Venkatesh 2021), will result in a win-win, enabling the attainment of several sustainability-related goals at once (Venkatesh 2023). However, one ought to always remember that there are no silver-bullet remedies to the challenges that we face. Regardless of which alternative one adopts, one cannot bring down the environmental footprint associated with that action to zero.

When we refer to 'environmental footprint', we are referring to a pot-pourri of adverse impacts. Fix one (Optimise one), and you would invariably end up sub-optimising another or a few others, at least a little bit. Weighting and prioritizing is availed of from time to time, depending on national policies, but they still do not really help one to address the issues from a long-term perspective. However, as it is always better to do something, and understand the challenges associated with compromising, life-cycle analysis (E-LCA) of products and processes is a well-entrenched tool which throws some light on how they perform vis-à-vis the environment (Gómez and Escobar 2022). The acronym E-LCA is used in this paper to differentiate it from S-LCA (social life-cycle analysis) which is also of interest when it comes to this comparison, but is beyond the scope of this particular review, even though the authors elaborate on user-perspective in the Discussion section. The focus in the article is narrowed down to gleaning from published reports and articles, the environmental impacts associated with grocery bags made of fossil-based LDPE and biobased paper The authors do not claim that this is a comprehensive review.

The articles reviewed for this paper were obtained by carrying out a literature search on Google Scholar. Search words that were used included a mix of "LCA, life cycle analyses, paper bags, plastic bags, LDPE bags, grocery bags". Around 10 different reports were picked out. These reports were superficially reviewed to find similar and divergent results between the different environmental impact categories. Other important factors that were decisive for the selections were where the E-LCA were located and if there was enough information about why the results may be different. Ultimately, five different E-LCA reports were selected, and they were different in the geographical location of the studied systems and also in some productions/raw material aspects. It must be mentioned that E-LCA is a flexible methodology, and allows analysts to define their goal and scope based on what they are keen on showing/proving/disproving/confirming. At times, thereby, results presented in two different papers cannot be compared directly without specifying the contrasts. The E-LCA reports that were studied did not use the same unites, since two used impact per bag, one used trip to supermarket and another one calculated the impact per bags used for an average annual consumption of groceries. Also, the reports used different assessment methods, with various quality. Kimmel (2014) and Stafford et al (2022) used ReCiPe and Dahlgren and Stipple used CML as the method. Anwar et al (2020) used openLCA as a tool for the study. Bisinella et al (2018) took data from the ecoinvent database and used ILCD2011. This makes it even harder to make a comparison between the different studies. However, the goal in this article is not to make a straightforward comparison between the E-LCA studies, but rather to study trends and make a generalized analysis.

1. Background facts about paper and plastic bags

1.1. The usage and properties of the carry-bags

Grocery bags – be they polyethylene (PE), paper or textile-based – are almost always used for transporting food and other products from supermarkets. As these bags do not have a long functional lifetime (most of them being single-use), it is imperative to ensure that they have a low contribution to the global warming (cradle-to-grave or cradle-to-cradle, if open/closed-loop recycling is involved). It follows that the 'size' of the environmental footprint with respect to the function provided during the use-phase (also called as the functional unit in E-LCA lingo), depends on the material of the bag, mode of usage, and end-of-life handling method/s (Bisinella et al. 2018). The function of course is paramount and must not be forgotten or relegated to the background, in the interest of the environment. In other words, the carry-bag must be robust and unbreakable. The user must be able to hold the bag comfortably, and it must, most importantly, protect its contents (food products most of the time) from moisture and dirt (Anwar et al. 2020).

1.2. Paper bag – manufacturing process

Paper bags are cellulose-based and trace their genesis primarily to wood, which is the most abundant, and thereby economical, source of cellulose in the world. As mechanical strength is a required property of a paper bag, sulphate pulp is the input of choice. The steps in the manufacturing process have been listed hereunder (Kimmel 2014):

- Bark removal from the logs,
- Logs converted to wood chips using a mechanical process,
- Suitably-dimensioned wood chips boiled in a solution of sodium hydroxide and sodium sulfide,
- Separation of lignin (80% of the lignin gets removed), resulting in a mass-yield of 45–50%,
- Cleaning and refining to produce a thick liquid, using a hydro-pulping process,
- Waste paper (received for recycling), in another part of the mill, is broken down to fibres; the fibres are cleaned, de-inked and refined,
- Papermaking process in which a mix of virgin fibres and recycled fibres can be used,
- The paper rolls (with or without recycled content), are sent to converters, who manufacture and print the paper bags, using hot melt glue, starch/dextrin, or polyvinyl acetate glue in the process.

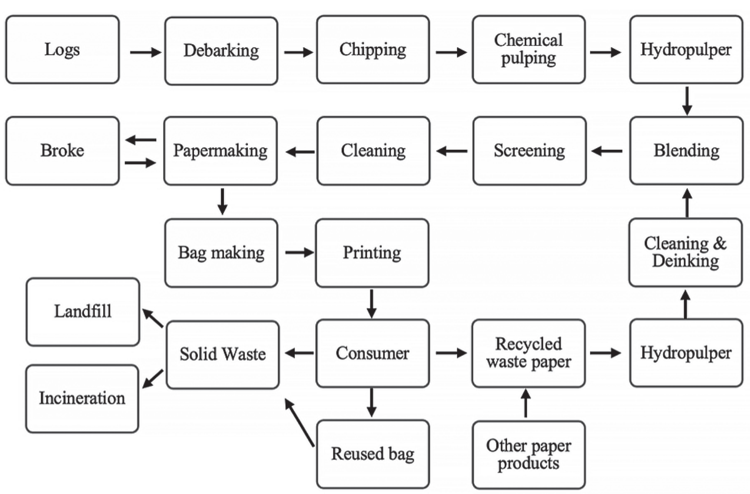

Figure 1. Diagram of Kraft paper bag life cycle (Adapted from Kimmel (2014)

1.3. LDPE-bags – manufacturing process

Low-density polyethylene or LDPE consists of long ethylene monomers obtained from steam cracking of ethane gas. Though LDPE can ideally be produced from renewable resources (a desirable future in a circular bioeconomy), at the time of writing, the source is predominantly crude oil or natural gas. The British Plastic Federation (BPF) has estimated that between 4 and 6% of all oil and gas in Europe is used to produce several types of plastics (starting from naphtha – the type of oil used in plastic production) (BPF 2019), of which close to 30% is polyethylene (Marcos 2016).

The steps in the LDPE production process have been listed hereunder (Browning 2021):

- Natural gas / crude oil is extracted and transported to a refinery,
- Fractional distillation separates petroleum into its different fractions,
- Once the required oil (naphtha, as referred to above) has been fractionated, it is superheated and pressurized,
- The pure polyethylene chains are then isolated and converted into resin pellets. LDPE is a more ductile and tough plastic, as the structure is linear with many short side chains, which inhibits crystallinity,
- The resin pellets are superheated and pressurized to form a liquid once again,
- Air is pumped into the liquefied LDPE and a balloon-like plastic film is formed,
- The film expands and cools, and as it cools it encounters several rollers that stretch and convert the plastic into very thin plastic sheets,
- The sheets are rolled up on large cylinders and sent to the printing press,
- Printing ink 'enters the fray' and flexographic printing labels the bags intended for supermarkets,
- Bags are formed when two printed sheets are pressed together at the edges, and sealed. They are then cut to the desired size.

While crude oil and natural gas were named as the raw materials for LDPE production at the start of this sub-section, it is also noteworthy to mention that the Fischer-Tropsch process can also be used to produce oil from coal – produced liquid hydrocarbons in the process (Stafford et al. 2022).

1.4. Differences in properties between plastic- and paper bags

While paper bags in general have a high load-bearing capacity, it has a lower tear strength and that implies a tendency to break if the bag is impaled by contents having sharp edges. It also is obvious that they are not waterproof, and if used in the monsoon, the contents in them, will in all likelihood, run the risk of getting spoiled/damaged. They are also heavier than plastic bags and occupy a little more space (for a given mass of contents carried). On the other hand, the plastic bag is more flexible, and even though there is a risk of its being damaged/punctured by sharp objects, its toughness ensures that it does not yield as easily as the paper bag.

LDPE, as such, is eminently recyclable (including closed-loop recycling), as its properties do not deteriorate as quickly as those of paper do. In an open-loop recycling system, paper can be recycled up to 7 times and it is usually downcycled into lower quality recovered paper products or incinerated for energy recovery (Ekhart 2021). LDPE can, in the presence of a sound recycling infrastructure, wait for a longer time before being downcycled or harnessed for its energy content. The mention of 'sound recycling infrastructure' is important here, as developing countries (and many others) currently lack the same. This augments the risk of plastics being consigned to dumpsites and landfills and ultimately ending up in oceans (refer Figure 2), affecting marine life adversely and resulting in biodiversity losses. Plastics break down into smaller (micro-) particles and spread out as microplastics, increasing the risk of exposure and the eventual endpoint (one of the three in the ReCiPe method

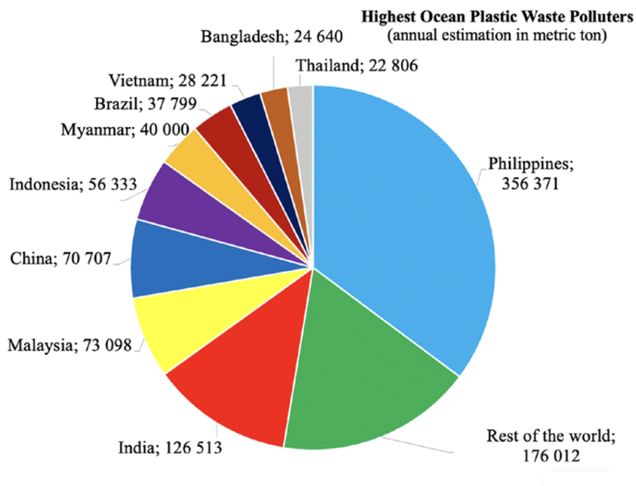

Figure 2. Ocean plastic waste polluters – the culpable parties in 2023. Adapted from a LinkedIn Post seen in March 2023 by the second author

in an E-LCA) – biodiversity or species losses (Bagitan Packaging 2022).

2. Findings from the focused review

As referred to earlier, this is a focused review which complies, compares, and contrasts results from five different E-LCA studies carried out in Sweden (Dahlgren & Stipple 2016), USA (Kimmel 2014), Europe (Anwar et al. 2020), South Africa (Stafford et al. 2022) and Denmark (Bisinella et al. 2018). The findings have been organized under different sub-sections hereunder, one for each of the environmental impact categories studied. In all the Tables, the green-shaded cells indicate the lowest (or lower, in case of just two different values) value reported in each of the articles reviewed. The higher values are compared to the lowest/lower ones by indicating the percentage increase in impacts (in the orange-shaded cells).

2.1. Global warming potential (GWP)

Table 1 presents the global warming potential (GWP) in terms of grams of CO_2-equivalents per product alternatively per trip to supermarket. The products, paper bags and LDPE bags, are either made of virgin fibres or plastic, or have different shares of recycled fibres or plastic.

In the Swedish study by Dahlgren and Stipple (2016), paper bags made from 85% recycled paper (RC) and 100% virgin fibre were studied. Here it shows that the bag with 85% RC gave a higher GWP-value than the virgin material. The production of virgin fibre consumes more energy than the production of recycled pulp. The reason why the virgin fibres have a lesser GHG-footprint in this case, is because of the energy resource that is being used. European average data was assumed for the manufacture of the recycled pulp, and natural gas dominated as the source of energy, explaining the higher GHG-footprint. In Sweden, for that matter, the energy sourced from the grid and utilized for the production of virgin-fibre paper bags is a mix of hydropower and nuclear energy, and this mix has a very low GHG-footprint. The residual electricity was in this case purchased from Vattenfall, and the mix considered of 50,5% nuclear power, 48,7% hydro power and 0,8% wind power. That gave a 7,3 g CO_2-eq / kWh (Dahlgren and Stipple 2016). The Swedish authors, as indicated in Table 1, also studied the GHG-footprint of 50%RC LDPE bags and LDPE bags made from biomass ('renewable' in the Table). The latter was sourced from bio-ethanol (extracted from sugar beets)

Table 1. Global warming potential for different compositions of paper bags and LDPE bags, taken from four different studies. ‘RC’ stands for recycled content

Material		Paper					LDPE		
Source	Units	Virgin	100% RC	85% RC	54,8% RC	40% RC	Fossil-based virgin	50% RC	Renewable virgin
Dahlgren & Stipple (2016)	GWP ($g\ CO_2$-eq/bag)	30		56				75	102
	% diff.			*+86.7%*				*+150%*	*+240%*
Kimmel (2014)	GWP ($g\ CO_2$-eq/trip to supermarket)		769			881	1270		
	% diff.					*+14.6%*	*+65.1%*		
Anwar et al. (2020)	GWP ($g\ CO_2$-eq/bag)	347					391		
	% diff.						*+12.7%*		
Stafford et al. (2022)	GWP ($g\ CO_2$-eq/*)				3209.8		7380.2		
	% diff.						*+129.9%*		

*Annual average consumption of groceries (870,479 l) from the supermarket to the home for a South-African inhabitant.

and manufactured in Brazil. Importing that into Europe incurs fossil fuel consumption for transport over a distance of around 10,000 kilometres or more. The contribution of the transport stage to the GHG-footprint is around 9.15 gCO_2 –eq /bag for the renewable LDPE bags (ca 10% of the total impact). Interestingly, for the virgin-fibre paper bag in the same study, the corresponding value was 7.42 gCO_2 –eq /bag (25% of its footprint), despite the much-shorter distance over which it is transported. The reason can be attributed to the fact that paper bags weigh more than LDPE bags and it would thereby consume more fuel (resulting in higher emissions) to move them around.

In the USA-study, Kimmel (2014) reported a value of 881 g CO_2 –eq / one trip to supermarket for paper bags with 40% recycled content, and a slightly lower value of 769 gCO_2 –eq / trip for alternatives with 100% recycled content. The high values for 40%RC is due to the fact that the production of new fibre pulp has a higher GHG-footprint because it demands more energy, and in the USA the electricity mix is dominated by fossil fuels. Comparing paper with LDPE, one notes from Table 1, that the LDPE-bag (without any recycled content) had a climate impact (which is alternately referred to as GHG-footprint) that was 1.65 times greater than that of the paper bag with fully recycled content. The LDPE bag, in this particular study, had a higher GHG-footprint manly because of the impact from the raw material extraction. Anwar (2020) reported a 12% higher GHG-footprint for LDPE bags over paper bags made from virgin fibres. It can be safely inferred that the lower mass of the former (18 grams per LDPE bag vis-à-vis 42 grams per paper bag) plays a role in truncating its GHG-footprint and narrowing the gap between it and its biotic counterpart. This highlights the importance of dematerializing by lightweighting (along with the use of policy instruments like single-use plastic taxes) in the journey towards sustainability.

The study done in South Africa by Stafford et al. (2022), reported a conspicuously-higher GWP vis-à-vis the other three. However, the results have to be interpreted with caution as advised earlier, as the scope would have been defined differently by the authors. In this study, the functional unit is an average person's annual grocery purchases (870.48 litres), and the emissions are corresponding to this functional unit. The annual per-capita consumption of the number of LDPE-bags and paper bags was calculated to be 36.27 and 43.59 bags, respectively. The LDPE bags weight 15.32 g and holds 24 litres. The amount of material used for one year's consumption is 555.66 g. As for the paper bag, it weighs 38.42 g and holds 19.97 litres. 1674.7 g of material is needed for one year's consumption. Both of these bags are considered to be used only once. A point to be noted here is that in South Africa, oil (and thereby naphtha for LDPE production) finds its source in coal, which is subjected to the Fisher-Tropsch process, which by virtue of being energy-demanding and dependent on coal, has a very high GWP.

2.2. Energy demand and dependence on fossil fuels

Kimmel (2014) has also compared 100% RC paper, 40% RC paper and LDPE across two additional criteria – Energy demand in terms of MJ/trip to supermarket and the depletion of fossil fuels in terms of g oil/trip to supermarket. Figure 3 presents the comparison by normalizing with respect to the least of the three values for these two criteria and also the GWP discussed in the previous section. 'Traffic-lighting' colour code has been used to visually depict the ranking for each of the three criteria – green (least impact and best result), orange (intermediate), and red (highest impact and worst result). While the GWP values per trip to supermarket have been indicated in Table 1 already, the energy demand in MJ/trip ranged from 10.1 to 34.5; and the depletion of fossil fuels in g oil/trip ranged from 207 to 706.

2.3. Water footprint

In Table 2, it is clearly seen that the water demand for the production of LDPE bags is lesser (in all the three studies). In paper production, sulphate pulping is a water-demanding process. Sulphate pulping is adopted when virgin fibres are being processed. There are differences in the amount of water usage, depending on the percentage of recycled paper. Kimmel (2014) has reported a 47.5% increase in water usage for paper bags per trip to supermarket with 100% recycled content, and a three-fold increase for paper bags with 40% recycled content, vis-à-vis virgin LDPE bags.

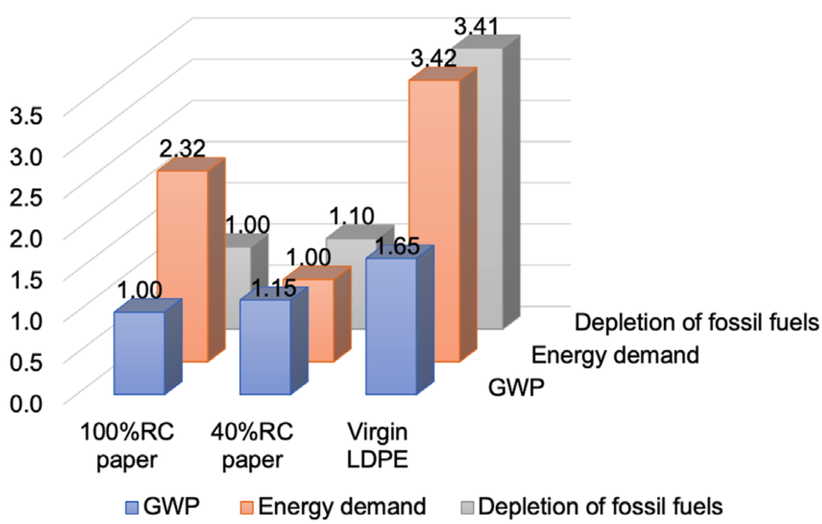

Figure 3. GWP, Energy demand and Depletion of Fossil fuels – three criteria compared for the three alternatives for carry-bags studied in Kimmel (2014)

Table 2. Water usage per trip to supermarket for paper (virgin and recycled) and virgin LDPE bags

Material		Paper				LDPE
Source	Units	Virgin	100%RC	54,8%RC	40%RC	Fossil-based virgin
Kimmel (2014)	Water use (liters/trip)		4.65		10.48	3.16
	% diff.		*+47.5%*		*+231.6%*	
Anwar et al. (2020)	Water use (liters/bag)	35.9				31.3
	% diff.	*+14.7%*				
Stafford et al. (2022)	Water use (liters/*)			67.1		39.1
	% diff.			*+71.6%*		

*Annual average consumption of groceries (870,479 l) from the supermarket to the home for a South-African inhabitant.

The explanation is the sulphate pulping process as mentioned above. The paper bag with 100% recycled content consumed only 7.5% of its total water footprint during the raw material production (cleaning, refining and deinking etc.) process.

2.4. Acidification potential (AP)

In three of the four studies represented in Table 3 above, paper bags have a lower acidification potential compared to their LDPE counterparts. In the Swedish study, while the acidification potential is much lower compared to the other studies in general, paper bags (with both virgin and 85% recycled content) have higher AP vis-à-vis LDPE with 50% recycled content. It is mentioned in the Swedish study that owing to the use of biofuels in the pulping process, the AP increases due to the emissions of nitrogen dioxide, sulphur dioxide and ammonia (which in turn result in the formation of sulphuric and nitric acids which are deposited on soils and in water bodies). The 15% virgin pulp content in the 85% RC paper bag, contributes to one-fourth of its AP.

What stands out in Table 3 is the 645% increase in AP for the LDPE produced

Table 3. Acidification potential (AP) for paper (virgin and recycled) and LDPE (fossil-based virgin, renewable virgin and recycled) bags

Material		Paper					LDPE		
Source	Units	Virgin	100% RC	85% RC	54,8% RC	40% RC	Fossil-based virgin	50% RC	Renewable virgin
Dahlgren & Stipple (2016)	Acidification (g SO_2/bag)	0.214		0.194				0.13	0.969
	% diff.	*+64.6%*		*+49%*					*+645%*
Kimmel (2014)	Acidification (g SO_2/trip)		1.63			3.65	13.6		
	% diff.					*+123%*	*+734%*		
Anwar et al. (2020)	Acidification (g SO_2/bag)	2.45					2.63		
	% diff.						*+7.3%*		
Stafford et al. (2022)	Acidification (g SO_2/*)				17.3		38.4		
	% diff.						*+122%*		

*Annual average consumption of groceries (870,479 l) from the supermarket to the home for a South-African inhabitant.

Table 4. Eutrophication potential (EP) for paper (virgin and recycled) and LDPE (fossil-based virgin, renewable virgin and recycled)

Material		Paper		LDPE		
Source	Units	Virgin	85% RC	Fossil-based virgin	50% RC	Renewable virgin
Dahlgren & Stipple (2016)	Eutrophication (g PO_4^{3-}/bag)	0.0936	0.0545		0.0192	0.4272
	% diff.	*+388%*	*+184%*			*+2125%*
Anwar et al. (2020)	Eutrophication (g PO_4^{3-}/bag)	0.137		0.391		
	% diff.			*+185%*		

from renewable sources vis-à-vis the 50% RC LDPE. This again can be attributed to the production of ethanol from sugar beet, and the associated emission of ammonia. About 80% of the AP in this case is attributable to upstream material production, with transport adding as much to the AP footprint, as the total AP of the bags made of paper.

While the Swedish authors studied LDPE with 50% recycled content, and LDPE made from sugar-beet-ethanol, the others focused on virgin LDPE (originating from naphtha). In the other three studies, the AP of virgin LDPE is between 7.3% and 734% greater than the corresponding lowest value for paper bags (100% virgin fibres or with recycled content). For the LDPE bag in the study by Kimmel (2014) there is roughly an eight-fold increase in AP vis-à-vis the paper bag with 100% RC. This is because they have included that LDPE bags are responsible in the upstream production process, for the release of acidifiers to the soil (sulphur dioxide especially, owing to the sulphur content of the oil they are produced from). Stafford et al. (2022) have recorded a greater difference between the AP of paper bags and that of LDPE bags, as compared to Anwar et al. (2020), owing simply to the fact that the Coal-to-Liquids (CTL) Fisher-Tropsch process in the South African study is a big contributor to acidification.

2.5. Eutrophication potential (EP)

Quite similar to GWP and AP, the renewable LDPE bag recorded a very high EP, vis-à-vis the 50% RC LDPE which turned out to be the least among the four alternatives studies by Dahlgren & Stipple (2016). This, one can attribute to the use of NPK fertilisers, which when used in excess of their requirement and uptake by the sugar beet plants, tend to get leached out to water bodies from the soil, and cause eutrophication. Further, release of ammonia to the atmosphere from the soil can lead to its dissolution in water bodies elsewhere – an indirect cause of eutrophication. The paper bags in the Swedish study resulted in 388% (for virgin fibres) and 184% (for 85% recycled content) greater EP vis-à-vis 50% RC LDPE, owing to the release of nutrients (nitrogen, phosphorus) and COD even after wastewater treatment at the paper mills. Efforts are underway at paper and pulp mills in Sweden, to augment the wastewater treatment process to increase the degree of removal of nitrogen, phosphorus and COD from the effluent. Anwar et al. (2020) have reported a 185% higher EP for virgin LDPE as compared to its virgin paper counterpart, by reasoning out that 80% of all these bags end up in landfills, and by virtue of being 'COD', end up causing eutrophication in the medium-to-long term, when they would leach out to water bodies. However, while the landfill argument holds for the developing world countries, it is a bit uncertain whether that is the fate of LDPE bags in the developed world, where a good deal of them would tend to be incinerated – with or without energy recovery.

2.6. Toxicity potentials – human, terrestrial, freshwater-aquatic and marine-aquatic

Figure 4 compares the different toxicity potentials for three alternative materials, as reported by Kimmel (2014). The method that was used was World ReCiPe Midpoint H/A V1.07. Quite similar to Figure 3, the values are normalized with respect to the least value in each category, and 'traffic-lighting' colour code is adopted to show the ranking visually. The virgin LDPE bag by far causes the highest toxicity-related impacts (for three of the four types), while the 40% RC paper bag is a larger contributor to terrestrial (or soil) toxicity than the other two alternative materials. In terms of g 1,4-dichlorobenzene/trip to the supermarket, human toxicity potential (HTP) varies from 116 to 523; terrestrial eco-toxicity potential (TETP) varies from 0.072 to 0.163, freshwater aquatic eco-toxicity potential (FAETP) varies from 3.22 to 23.8, and marine aquatic eco-toxicity (MAETP) ranges between 2.26 and 23.1. Figure 5 (Venkatesh 2016) is a generic depiction of how toxicity-related impacts can be understood – from a cause-effect point of view, or a source-route-impact point of view.

2.7. End-of-Life (EoL) management alternatives

While the four articles referred to above, focused more on the upstream production of the paper and LDPE bags, Bisinella et al. (2018) which is a Danish study, dwelt on the various end-of-life management options available for grocery bags – incineration, recycling, and reuse as garbage bags. They compared bleached and unbleached paper bags, with virgin LDPE and 50% RC LDPE. The virgin LDPE bag is considered as the 'reference product', and it is noted that owing to the difference in mass and load-bearing strength, two 50% RC LDPE and two paper bags are needed to carry the same amount of goods as one virgin LDPE bag. For the 50% RC-LDPE case, data pertaining to virgin LDPE were assumed as proxies, because no data could be obtained for the production of recycled LDPE, by these authors.

The unbleached paper bag was shown a better environmental impact than the bleached paper bag, for all EoL options, owing to the fact that the production of the bleached paper is more energy demanding. Recycling a paper bag entails additional energy use, which results in GHG emissions, while reusing it as a garbage bag

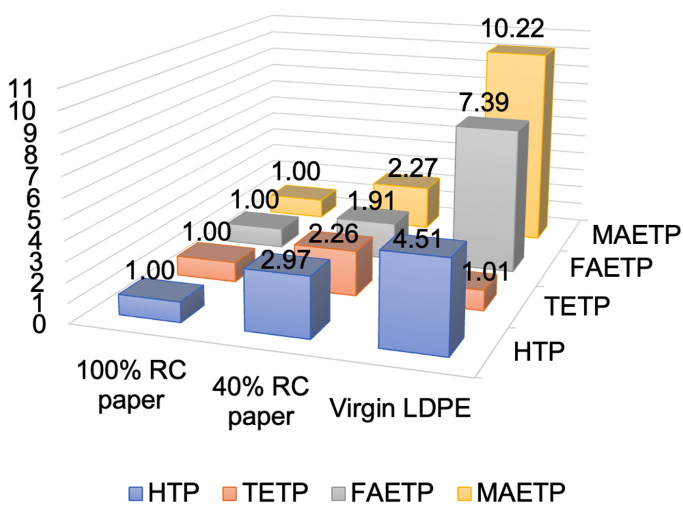

Figure 4. Toxicity potentials – HTP, FAETP, TETP and MAETP – for three alternative materials for paper bags [modified based on results from Kimmel (2014)]

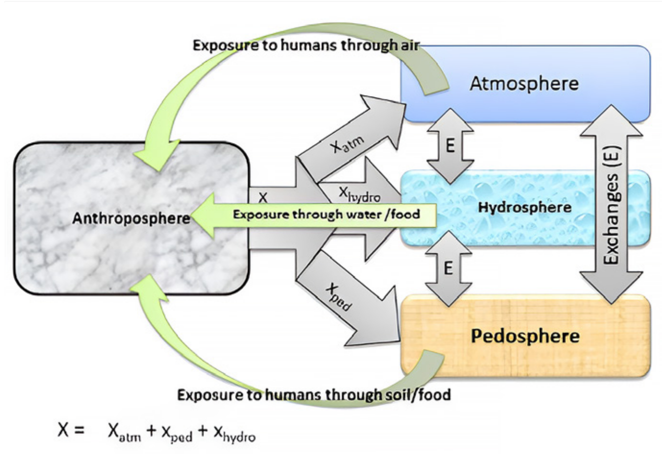

Figure 5. Visualization of toxicity-causing emissions from a product's lifecycle (in this case, paper or LDPE bags) from the techno-anthroposphere to any of the environmental media, exchanges among them, and a rerouting back to the source, to affect the emitters (Venkatesh 2016)

has the lowest GWP, owing to the emissions avoided by not having to use a new LDPE bag (the reference bag is made of virgin LDPE in this study). If the reused bag is an unbleached paper bag (which obviates the need for a new virgin LDPE bag), a net reduction in GWP is achieved. A virgin LDPE bag has a lower GWP value for all the EoLs, as compared to the 50% RC LDPE bag, precisely because functionally, one virgin LDPE bag is equivalent to two 50% RC LDPE bags. When LDPE bags are incinerated, the carbon in the polymer is oxidized to carbon dioxide and contributes to global warming. When it is recycled, the GWP is lower than when they are incinerated. It is the lowest when the bags are reused (or more appropriately repurposed as garbage bags – a much-needed behaviour change, recommended in a more circularized economy in the future).

Conclusions: take-home messages and recommendations

While the review focused primarily on a selected few E-LCA publications which dealt with a comparison among paper and LDPE bags (and such publications obviously are not very many in number), this paper can leave the reader with some points to ponder over:

It is important to know that many factors affect the results in the E-LCA. In this report we can clearly understand that size and weight of the bags, energy source used for production, raw material (recycled or virgin) and transport distance have a big impact on the different parameters that were studied.

When the tax on single-use plastic bags was introduced in Sweden in 2020, some people were upset because of the higher price (Dahlin 2020). What could not be brought about by choice (a soft awareness-generation approach) had to be done the harder way. It led to a conspicuous change in behaviour, and a much needed one at that,

Sweden has an established recycling system which has the capacity to materially recycle larger volume of LDPE and other types of common plastic materials than it recycles today. However, most of the plastic is still incinerated for energy recovery which may be questionable from a circularity point of view (Naturvårdsverket n.d.b),

In the developing countries, it is uneconomical to collect and recycle plastic bags, which instead end up in nature, e. g. in the marine environments causing biodiversity losses (Gómez and Escobar 2022),

Plastics need not be looked upon as 'villains' per se. Rather, it is how we (who 'created' the plastics in the first place) handle them that determines how detrimental they are. If recycling infrastructure is developed at a brisk pace, the circularity that would induce would relieve plastics a great deal of the notoriety that has come to be associated with them,

Paper may not be a silver-bullet replacement solution for plastics, after all! Despite the fact that the paper bag had a better result overall, the plastic bag is still considered positive since the raw material has a better potential to be recycled and recreated (if the infrastructure allows it), than paper which can be recycled up to seven times in an open-loop system. However, for plastic to be beneficial, a closed cycle must be created,

Unlike plastics which can be recycled several times, given the infrastructure and the will to do so, paper cannot be. Paper bags also weigh more than plastic bags, and that increases the climate impact caused by transportation,

As long the environmental externalities, such as e.g., cost of littering, are left out of decision-making, what is detrimental to the environment will remain more affordable and therefore preferred by consumers, leading to an increase in revenues and higher profits for the producer (and more tax receipts for the government),

It is not just global warming and the consequent climate change that must attract attention and redressal but other environmental impacts as well in terms of a multi-criteria sustainability assessment,

The socio-economic aspects of the life cycles of products like the ones studied in this paper need to be accorded as much importance as the environmental ones.

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